Elliott Bay Design Group

NEW VEHICLE FERRY
M/V WOODS HOLE EQUIVALENT

Hybrid Propulsion Study

Prepared for: Steamship Authority |Falmouth, MA

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REVISIONS

REV	DESCRIPTION	DATE	APPROVED
-	Initial Issue	4/14/22	LGB 51201
A	Revised to align shore power electricity costs with KPFF memo.	5/13/22	LGB 51201
B	Revisions to address comments / suggestions from the Martha's Vineyard Committee, Reference 1.	3/27/23	LGB 51201

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1. PURPOSE

This study presents a comparison of alternative propulsion options for a New Vehicle Ferry. The vessel considered in this study is an equivalent of the M/V WOODS HOLE with alterations for alternative propulsion configurations. This equivalent vessel is 235 ft. x 64 ft. x 18.5 ft. passenger ferry intended for service on two routes operated by the Steamship Authority (SSA): Woods Hole to Martha's Vineyard and Hyannis to Nantucket.

1.1 REVISIONS

Following the initial release of the study, the Martha's Vineyard Commission Climate Action Task Force (MVC) prepared their concerns and assessment of the report [1]. The MVC provided the study team with a list of ten suggestions and requests for modifications to the parameters used in this report. Below is a simplified list of these suggestions and how each suggestion is or is not addressed by this revision:

1. **Develop cost estimates that are representative of a total vessel build.** Revision B of this study incorporates a full vessel cost estimate with reference to the construction cost estimate for the M/V WOODSHOLE, [2]. Note that in 2014, this construction cost estimate was $41.3 million and the awarded contract was for $36.4 million.

2. **Consider a Plug-In Hybrid**

    a. **Analyze the feasibility of a plug-in hybrid for the optimal hybrid-electric configuration.** Revision B of this study incorporates a plug-in hybrid option for the Martha's Vineyard Route. Because shoreside charging facilities are not considered for the Hyannis to Nantucket route, this option is not sized for that route.

    b. **Consider the possibility of vessels with the technical capability to be converted from diesel-mechanical to plug-in hybrid electric to all-electric over the course of vessel useful life.** This comment is not addressed by Revision B. Conversion from diesel-mechanical architecture to diesel-electric hybrid architecture is complex; if there is a future desire to add battery capacity, a vessel design should incorporate design features that support that conversion. Hybrid vessels have different regulatory requirements, require additional hull compartments, and tend to have more complex cooling systems. Additionally, the weight change expectations would need to be considered at the outset of the design.

3. **Increase the time frame of the study from 10 years to 20 years.** Revision B of this study increases the operational cost study from 10 years to 20 years.

4. **Revise energy price modeling.** In the previous revision of this study EBDG used a 3% inflation rate for all energy costs. Based on the Energy Information Association's 2023 Annual Energy Outlook [3], diesel cost is expected to grow at a rate of 2.4%, while electricity rates are expected to grow 2% through the year 2050. These rates are used in Revision B of this study. KPFF has provided Reference [4] to provide additional insight here.

5. **Compare expected maintenance costs for diesel-mechanical v hybrid-electric v all electric options with SSA actuals as a baseline.** The actual maintenance data from SSA is not discrete enough for this study. The previous and current version of this report utilized maintenance cost

projections from MTU based upon engine operating hours; this data was scaled for each option's expected operating hours for engines/generators. Additional vendors were consulted for expected annual maintenance figures.

6. **Revise Battery Pricing Range**

    a. **Consider battery price replacement over twenty-year cost analysis.** Revision B of this study considers a battery replacement cost at 10 years as an overhaul expense.

    b. **Include battery replacement cost as NPV only (capital cost not operating cost).** The previous version of this study considered a ten-year battery replacement cost spread over 10 years represented as an annual cost. As noted above, Revision B considers a battery replacement cost at 10 years. Additionally, Revision B considers engine / generator repowers at 10 years.

    c. **Use a cost analysis approach similar to WSF (significant cost reduction over time).** The WSF study occurred earlier in the timeline of US based vessel electrification and hybridization studies and thus saw a dramatic cost reduction for marine rated batteries. WSF was initially quoted $1100/kWh in 2011 and this dropped to $650/kWh when purchasing a volume of at least 1MWh. In the previous version of this study, EBDG used $750/kWh based upon discussions with a battery manufacturer. For Revision B of this study, this figure is revised to $650/kWh based upon discussions with the same battery manufacturer. While EBDG expects that the energy density of batteries will increase with technological advancements, it seems the cost per kWh has stabilized relative to historical trends.

7. **Develop monetized value of emissions reduction.** This is not addressed in Revision B as it is not within the scope of this study. This is a topic that could be addressed by a broader study that takes into consideration the communities served; the Hybrid Propulsion Study scope is limited to potential vessel installations.

8. **Capital Cost Vetting.** EBDG hired a third-party consultant to prepare an independent capital cost assessment for each of the proposed propulsion options. The consultant was provided with a redacted version of the previous revision of this study to define the different propulsion options. The consultant also had access to the 2014 M/V WOODS HOLE construction cost estimate. Reference [5] is provided to address this comment. KPFF also had the shoreside capital costs assessed by a third party consultant, this is addressed in Reference [4].

9. **Research available federal funds.** This is not addressed by Revision B. The scope of this study is to provide the cost of the different options. Research into available funding sources should be the subject of a separate study.

10. **Establish a SST Strategic Plan.** This is not addressed by Revision B as it is not within the scope of the Hybrid Propulsion Study.

2. PROCEDURE

2.1 OVERVIEW

SSA provided operational vessel data from the M/V WOODS HOLE from the past five years while operating on the two routes. This data was reviewed and sorted to construct propulsion and hotel load profiles for each route. Six different propulsion configurations were identified as options for this vessel and each configuration was evaluated in terms of three evaluation criteria: capital cost, operating cost, and emissions.

2.2 CANDIDATE PROPULSION SYSTEMS

Preliminary discussions between EBDG and SSA led to the selection of six different propulsion arrangements for evaluation over two different routes. See Appendix C for system arrangement sketches.

2.2.1 OPTION 1: DIESEL MECHANICAL

The diesel mechanical option is meant to represent an updated version of the M/V WOODS HOLE installation and act as the baseline for all the other options. The configuration is a standard diesel mechanical propulsion system with two independent propulsion trains each with a high-speed diesel engine driving a single controllable pitch propeller (CPP) via a reduction gear and conventional shaft line. Electrical ship service power is provided by three diesel generators.

For this option the following equipment was considered:

- Two MTU 16V4000 M65L EPA Tier IV propulsion engines, rated for 2560 kW
- Two Hundested CPP Systems, including marine gear boxes and propeller units
- Three John Deere 6135 AFM85 diesel generators, rated for 310 ekW

2.2.2 OPTION 2: BERTH BATTERY

The second configuration is a diesel hybrid propulsion system with electric propulsion motors, generators, and battery banks. Three high-speed diesel propulsion generators are provided to charge batteries, provide hotel power, or power electric propulsion motors. Two variable speed propulsion motors would then drive fixed pitch propellers. Electrical ship service power is provided by the battery bank and the propulsion generators. Note that the third propulsion generator is included in this option, and all other hybrid options, in order to provide operational redundancy similar to the M/V WOODS HOLE configuration with three ship service generators.

This configuration is sized such that the diesel generators provide for propulsion and hotel loads during the crossing while charging batteries. In berth at either end of the crossing all diesel generators are shut down and hotel loads are provided by the battery banks.

For this option the following equipment was considered:

- Three MTU 16V4000 M65L EPA Tier IV generators, rated for 2450 ekW
- Two fixed pitch propellers

- Two 1,000 kW electric propulsion motors
- A DC propulsion switchboard, AC distribution switchboard and all interfacing equipment
- 180 – 190 kWh batteries

2.2.3 OPTION 3: PEAK SHAVE

The third configuration is a diesel hybrid propulsion system similar to Option 2 with an increased battery capacity. This configuration is optimized to level load the generators throughout the route, removing any peak demands from the generators operational profile and increasing the overall efficiency of the generator. Batteries are charged and discharged to support the level loading of the generators. The generators operate while in the berth.

For this option the following equipment was considered:

- Three MTU 16V4000 M65L EPA Tier IV generators, rated for 2450 ekW
- Two fixed pitch propellers
- Two 1,000 kW electric propulsion motors
- A DC propulsion switchboard, AC distribution switchboard and all interfacing equipment
- 1,500 – 1,900 kWh Batteries

2.2.4 OPTION 4: 50% BATTERY (MANUEVERING AND BERTH BATTERY)

The fourth configuration is yet another diesel hybrid propulsion system with additional batteries beyond those provided in Option 2 and Option 3. In this configuration diesel generators provide for propulsion and hotel loads and charge batteries during the transit portion of the crossing. The batteries are then used to provide for propulsion and hotel loads when the vessel is maneuvering in and out of the terminals. Additionally, batteries are used for hotel loads while in the terminal. The diesel generators will not operate while in berth.

For this option the following equipment was considered:

- Three MTU 16V4000 M65L EPA Tier IV generators, rated for 2450 ekW
- Two fixed pitch propellers
- Two 1,000 kW electric propulsion motors
- A DC propulsion switchboard, AC distribution switchboard and all interfacing equipment
- 1,800 – 2,500 kWh Batteries

2.2.5 OPTION 5: ALL ELECTRIC

The fifth propulsion option is an all-electric arrangement with battery banks sized to provide all propulsion and hotel loads for the entire crossing. Batteries are sized assuming they are charged to their full capacity after each one-way crossing. The batteries would be charged at both the Woods Hole and Martha's Vineyard docks. The Hyannis to Nantucket route is not being considered for all-electric propulsion at this time. A high-speed diesel generator is provided to charge batteries or drive electric motors should shore power be unavailable.

For this option the following equipment was considered:

- One MTU 16V4000 M65L EPA Tier IV generator, rated for 2450 ekW
- Two fixed pitch propellers
- Two 1,000 kW electric propulsion motors
- One DC propulsion switchboard, one AC distribution switchboard, and interfacing equipment
- One shore power terminal and interfacing equipment
- 5,400 kWh Batteries

2.2.6 OPTION 6: PLUG-IN HYBRID (50% DIESEL POWER, 50% SHORE POWER)

The sixth propulsion option is a plug-in hybrid arrangement with a battery bank sized to provide approximately half the propulsion and hotel loads via generators and half the loads via shore power. Batteries are sized assuming they are charged to their full capacity after each one-way crossing. The batteries would be charged at both the Woods Hole and Martha's Vineyard docks. The Hyannis to Nantucket route is not being considered for plug-in hybrid propulsion at this time. Two high-speed diesel generators are provided in this configuration which can be used to charge batteries and/or drive electric motors in certain operating modes.

For this option the following equipment was considered:

- Two MTU 16V4000 M65L EPA Tier IV generators, rated for 2,450 ekW
- Two fixed pitch propellers
- Two 1,000 kW electric propulsion motors
- One DC propulsion switchboard, one AC distribution switchboard, and interfacing equipment
- One shore power terminal and interfacing equipment
- 2,800 kWh Batteries

2.3 EVALUATION CRITERIA

2.3.1 CAPITAL COST

Capital costs consist of the purchase price of all major equipment for each propulsion option. Budgetary estimates from vendors along with cost data from prior studies were used to develop the capital cost estimates, with all costs presented in 2022 dollars.

A high-level cost estimate of the overall vessel construction cost was performed. This includes an estimation of inflation adjustments for typical vessel cost breakdowns (hull and superstructure, materials, electrical system, auxiliary systems, outfitting, engineering, shipyard support, etc.) from the original Woods Hole vessel construction [2]. Aside from the propulsion and powering systems, the costs associated with construction are expected to be relatively similar across all options.

2.3.2 OPERATING COST

The operating costs consist of a 20-year life cycle and include maintenance, energy, and engine/genset overhauls and battery replacement costs.

The maintenance cost includes the parts, consumables and labor for the recommended maintenance practices provided by the major equipment vendors. Maintenance activities were determined based

upon engine and gear operating hours. For the hybrid and all-electric options, battery replacement is included and based upon a 10-year battery life. Maintenance costs for standby equipment is also included; annual time to verify the functionality of equipment and maintenance materials is estimated.

The energy cost is based upon an estimated annual fuel consumption and annual shoreside electricity consumption. Energy consumption is based upon the route profiles described in Section 3.1. Shoreside electricity consumption is considered for the all-electric Option 5 and plug-in hybrid Option 6 with rapid charging connections available at the Martha's Vineyard terminal and the Woods Hole terminal.

Engine and generator set replacements are accounted for at the 10-year vessel operating mark, in line with the expected life cycle of that equipment. Engine repower is typically depicted as an operating cost in cost estimating applications, as these are expected expenses over the life cycle of the vessel. Costs are those associated with the price of equipment, materials, and labor at time of purchase. Similarly, a 10-year battery replacement in line with manufacturer rated life cycle and capacity is expected.

2.3.3 EMISSIONS

Once annual fuel consumption and operating hours for each arrangement is calculated the estimated annual Carbon Dioxide (CO_2), Nitrous Oxide (NOx), Carbon Monoxide (CO), and Particulate Matter (PM) emissions can be calculated. This study only considered vessel emissions and does not account for offsite emissions such as those associated with electrical power generation. Emission rates at various engine/generator loadings were used along with the calculated vessel power demand to generate a total amount of emissions per cycle.

3. GIVEN AND ASSUMED PARAMETERS

3.1 VESSEL ROUTE AND POWER REQUIREMENTS

Two routes were studied to determine propulsion system configurations and sizing. Operational engine data from the Woods Hole to Martha's Vineyard and Hyannis to Nantucket routes was analyzed to determine powering requirements for each route. The M/V WOODS HOLE operated on three distinct routes for the time frame analyzed: Woods Hole to Martha's Vineyard, Hyannis to Nantucket, and Woods Hole to Oak Bluff. The Woods Hole to Oak Bluff route was omitted from the analysis, as it is similar in powering to the Martha's Vineyard route and was not within the scope of study.

Port and starboard main engine data was submitted by MTU as a percentage of the engine's Maximum Continuous Rating (MCR). Figure 1 is an example of the data provided; this figure shows a single engine load as a percent MCR over a single run on the Martha's Vineyard Route.

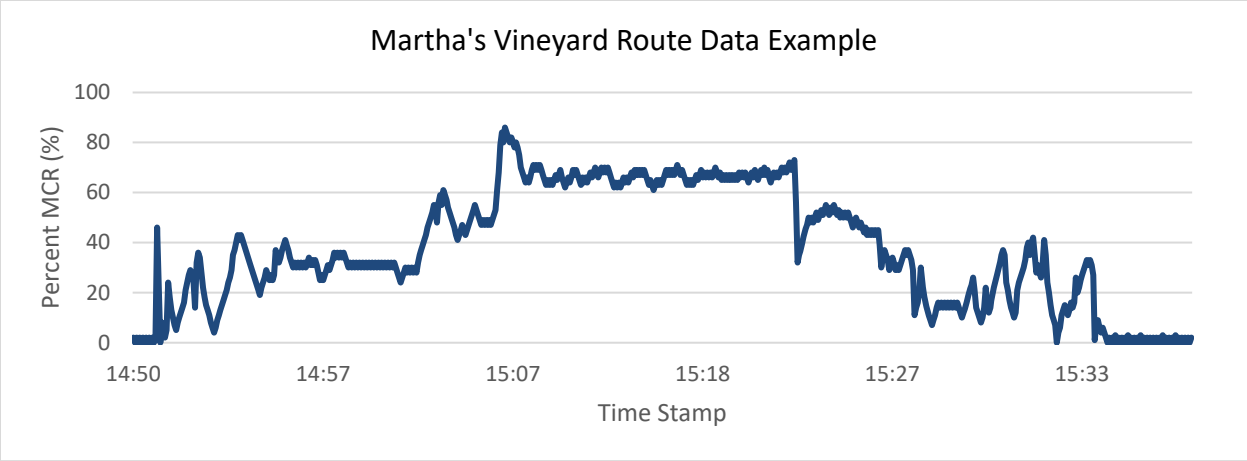

Figure 1: Example Propulsion Engine Data

The propulsion engine data was filtered to a representative day per month for each engine to account for differences in wind, wave, and loading conditions. SSA provided the approved vessel schedule as well as out of service dates for the vessel which was used to align the vessel activity with the data provided.

The values of the percentage load were averaged together as a piecewise function highlighting the different maneuvering and transiting conditions of the vessel during a typical voyage. The results of the data analysis were an average time and power spent at each operating condition for both the Woods Hole to Martha's Vineyard route and the Hyannis to Nantucket route.

3.1.1 WOODS HOLE TO MARTHA'S VINEYARD

The Woods Hole to Martha's Vineyard route has three distinct operating conditions: maneuvering out of the terminal, transit speed, and maneuvering into the new terminal. For annual calculations the vessel is assumed to operate on this route about 285 days per year with an average of 7 round trips per day. Figure 2 and Table 1 summarize the nominal Woods Hole to Martha's Vineyard route profile.

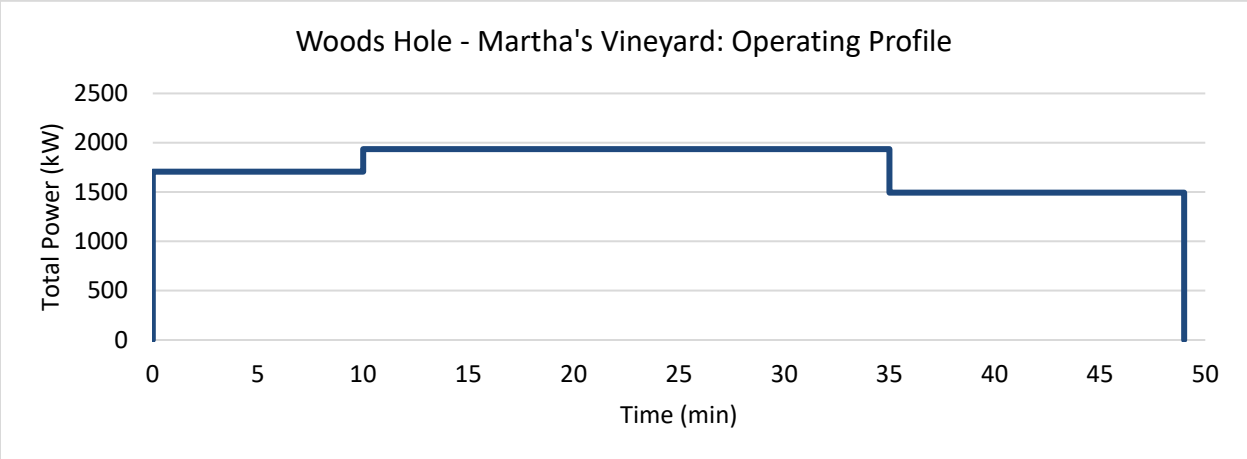

Figure 2: Woods Hole to Martha's Vineyard Profile

Table 1: Operational Profile - Woods Hole to Martha's Vineyard

OPERATING CONDITION	TIME (MIN)	COMBINED ENGINE POWER (KW)
Maneuvering 1	10	1707
Transit 1	25	1935
Maneuvering 2	13	1494

3.1.2 HYANNIS TO NANTUCKET

The Hyannis to Nantucket route has a secondary transit loading where additional power is required to maintain the transit speed. For annual calculations the vessel is assumed to operate on this route 200 days per year, 3 round trips per day. Figure 3 and Table 2 summarize the Hyannis to Nantucket nominal route profile.

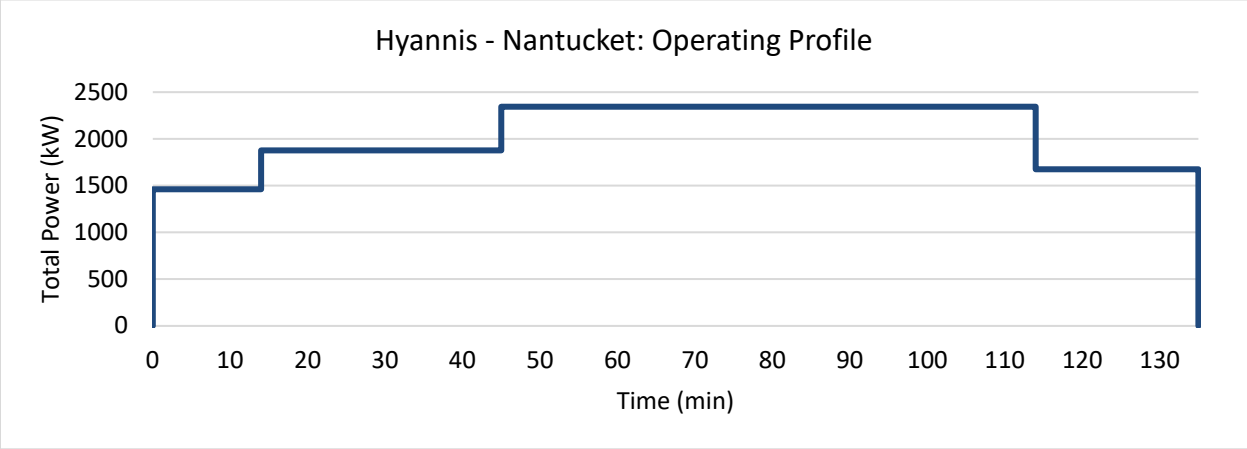

Figure 3: Hyannis to Nantucket Profile

Table 2: Operational Profile - Hyannis to Nantucket

OPERATING CONDITION	TIME (MIN)	COMBINED ENGINE POWER (KW)
Maneuvering 1	14	1460
Transit 1	31	1875
Transit 2	69	2344
Maneuvering 2	20	1674

3.2 SHIPS SERVICE ELECTRICAL AND HVAC REQUIREMENTS

Hotel loads of the existing vessel were analyzed in a similar fashion to the propulsion engine loads. After reviewing a collection of generator load data across a variety of dates for each route analyzed a conservative estimate was made.

For the purpose of this study, the assumed ships service electrical load is route dependent, with the Woods Hole to Martha's Vineyard route requiring 95 kW and the Hyannis to Nantucket route requiring

120 kW. These hotel loads account for lighting, ventilation, fluid pumping, and other normal operation loads.

All arrangements assume heat is supplied by a hot water boiler system and the propulsion arrangement will not affect the heat required by the vessel. Boiler fuel consumption is not included in the calculations.

3.3 FINANCIAL ASSUMPTIONS

For the capital and operating cost estimates, the following assumptions were used:

- Major equipment costs are based on quotes and costs derived from equipment vendors.
- Where current quotes were not obtained, equipment costs were estimated using a parametric approach, using that system's main design driver as the scaling factor.
- For the life cycle cost estimate, all costs were estimated as annual costs. In most cases inflation was assumed to be 3%, a value that has generally aligned with maritime and marine related assets over time. For diesel and electricity costs, specific inflation rates were used based on the Energy Information Association's 2023 Annual Energy Outlook [3]. Diesel is expected to grow at a rate of 2.4%, while electricity rates are expected to grow 2% through the year 2050.
- Electricity Rates were obtained from a study performed by KPFF, an engineering firm specializing in shoreside infrastructure. See References [6] and [4]. A single electric vessel was assumed to be charging directly from the grid.
- The consumables in Table 3 were assumed for the life cycle and fuel cost comparisons.

Table 3: Cost of Consumables

ITEM	COST	UNITS
Fuel (ULSD)	2.15	$/gal
Lube Oil	8.00	$/gal
Batteries	650	$/kWh
Urea	3.23	$/gal

- Ultra-Low Sulfur Diesel (ULSD) price was sourced from the 2021 actual expenses for the M/V WOODS HOLE. While this may not be reflective of the current spike in fuel costs, it is reflective of the highest cost per gallon since 2016.
- The cost per kWh for marine batteries is assumed to be $650/kWh. This value was confirmed with a maritime battery vendor during revisions to this report.

4. DISCUSSION

4.1 CAPITAL COST

The capital cost estimates for each propulsion configuration are provided in Table 4 and Table 5. Additional details of the Capital Cost Calculations are shown in Appendix A.

The cost estimate has been updated to consider the total vessel cost, including the cost of propulsion machinery. In 2014, EBDG performed a cost estimate of the M/V Woods Hole, [2], prior to construction. The estimate performed well relative to the final contract price (est. $41.3 mil vs awarded $36.4 mil) and is used as a baseline for the cost estimate performed for this study.

The EBDG Construction Cost estimate values were adjusted to include a 3% inflation between 2014 and 2023. The propulsion cost estimates were adjusted to reflect the entire estimated cost for a typical 200 level SWBS estimate (Propulsion Machinery – including but not limited to: prime movers, propellers, gears, support systems for propulsion machinery, etc.). Beyond inflation adjustments, the other SWBS level values are assumed to remain reasonably static under the assumption that a similar hull and arrangement are used.

For the propulsion option costs, high-level costs related to the propulsion system were addressed. In the diesel mechanical configuration, the capital costs accounted for the engines, the CPP system and reduction gears, and the ship service generator. Each of the diesel hybrid options had similar cost estimating, with the main differences in the costs being quantity of batteries required.

Of the diesel hybrid options, it is notable that the plug-in hybrid option and the 50% battery option have similar costs. The removal of a propulsion generator is offset by the cost of the shore power receptacle. The all-electric configuration was the most expensive of all the configurations. This can be attributed to its large battery storage requirements, its shore power charging connections, and the general powering redundancy necessary for regulatory approval.

The costs for the Martha's Vineyard route configurations are more expensive than the Nantucket configurations for Peak Shave and 50% Battery, as the number of annual cycles affects battery aging and increases the required battery capacity.

Table 4: Martha's Vineyard Full Vessel Capital Cost Summary

OPTION	DESCRIPTION	COST
1	Diesel Mechanical	$ 53,602,000
2	Berth Battery	$ 58,496,000
3	Peak Shave	$ 60,114,000
4	50% Battery	$ 60,690,000
5	All Electric	$ 61,461,000
6	Plug-In Hybrid	$ 60,636,000

Table 5: Nantucket Full Vessel Capital Cost Summary

OPTION	DESCRIPTION	COST
1	Diesel Mechanical	$ 53,602,000
2	Berth Battery	$ 58,551,000
3	Peak Shave	$ 59,793,000
4	50% Battery	$ 60,091,000

Cost estimations for both the vessel construction cost and propulsion options were sought by a third-party as a method of vetting EBDG calculations. The values found by the third-party were in line and within reasonable margins from EBDG values [5].

4.2 OPERATING COST

Each propulsion configuration was projected out to a 20-year span, with estimates for the major costs incurred during that 20-year period. The major drivers of the operating costs were diesel consumption, shore power, urea consumption, battery replacement, and engine/generator replacement and

maintenance. A 3% inflation rate in line with the maritime industry's inflation trends was assumed and used to calculate the future costs incurred for most recurring operating expenses. Where applicable, market specific inflation rates were assumed (2.4% for diesel, and 2.0% for electricity).

Engine, generator, and battery overhauls were included and expected to occur at the 10-year operating point. Costs for these values were inflated versions of the estimates used during the capital cost estimate.

The operating costs over a 20-year period, in 2022 dollars, are shown in Table 6 and Table 7. Additional details of the operating cost calculation are provided in Appendix B.

Table 6: Martha's Vineyard 20-Year Operating Cost Summary

OPTION	DESCRIPTION	COST
1	Diesel Mechanical	$ 29,866,000
2	Berth Battery	$ 29,524,000
3	Peak Shave	$ 31,798,000
4	50% Battery	$ 32,358,000
5	All Electric	$ 33,864,000
6	Plug-In Hybrid	$ 32,115,000

Table 7: Nantucket 20-Year Operating Cost Summary

OPTION	DESCRIPTION	COST
1	Diesel Mechanical	$28,002,000
2	Berth Battery	$27,983,000
3	Peak Shave	$ 29,346,000
4	50% Battery	$ 30,142,000

4.3 EMISSIONS

Utilizing the power profiles presented in Section 3.1 and ship service electrical requirements presented in Section 3.2, each route's emission generation was calculated.

It is standard practice to measure emissions in metric units. CO_2 generation is a function of the diesel fuel burned; one metric ton of CO_2 is generated for every 99.4 gallons of diesel burned. All other emissions (NOx, CO, and PM) were calculated based upon load-weighted EPA emissions certification data provided by the engine manufacturers. NOx, CO, and PM emissions from marine engines are already controlled by EPA regulations and all engine manufacturers are required to provide documentation of their engines meeting the EPA regulations. Table 8 and Table 9 show the total annual emissions produced by each configuration option.

The all-electric configuration was assumed to produce approximately 5% of the emissions of the diesel mechanical arrangement. This was to account for occasional operation of the installed diesel generator. It is expected that the generator may be required for vessel propulsion, and it is good marine practice to ensure the generator is operable.

Table 8: Martha's Vineyard Emissions Summary

OPTION	DESCRIPTION	CO_2 (MT/YR)	NOX (MT/YR)	CO (KG/YR)	PM (KG/YR)
1	Diesel Mechanical	3849	22	909	175
2	Berth Battery	3565	14	258	87
3	Peak Shave	3538	13	467	82
4	50% Battery	3544	11	2118*	101
5	All Electric	187	1.1	45	8.7
6	Plug-In Hybrid	1615	5.3	774*	43.7

*These values are based on an emissions curve with limited information and a selected generator loading. If this arrangement is selected, it could be optimized for emissions.

Table 9: Nantucket Emissions Summary

OPTION	DESCRIPTION	CO_2 (MT/YR)	NOX (MT/YR)	CO (KG/YR)	PM (KG/YR)
1	Diesel Mechanical	3619	20	936	155
2	Berth Battery	3355	13	364	79
3	Peak Shave	3317	11	1782*	92
4	50% Battery	3336	12	968	81

*This value is based on an emissions curve with limited information and a selected generator loading. If this arrangement is selected, it could be optimized for emissions.

5. CONCLUSIONS

Of the six options considered, Option 1 (diesel mechanical) produced the most emissions and was the cheapest propulsion configuration. Option 5 was the closest to zero emission (wake-side) configuration and was also the most expensive to procure. The diesel hybrid options (Options 2-4) produced emissions similar to, but less than the diesel mechanical option with CO_2 emission reductions ranging from 7% - 8% depending on the load conditions of the propulsion generators. Option 6, the Plug-In Hybrid option had emissions approximately half those of the diesel-electric hybrid operations, but this is largely contingent on the amount of time the vessel is operating on stored power from shore power versus generator power.

Capital costs for the propulsion systems were higher the more emissions were reduced. The increase in cost amongst the hybrid and all electric options was largely related to the quantity of batteries needed in each powering scenario.

Future studies and analyses could be performed to better define a vessel optimized for an all-electric or hybrid option. There is likely a sweet-spot design that would work well on both routes. An all-electric configuration for the Hyannis – Nantucket route was not considered in this study, and the quantity of batteries for that application would likely be prohibitive. An evaluation of the existing M/V WOODS HOLE hold space for fit of a diesel hybrid propulsion configuration is recommended.

This study did not consider any alternate fuels such as methanol, hydrogen, or ammonia as potential vehicles for emissions reduction relative to diesel. To do so would require an in-depth analysis of the supply chain of such fuels.

6. REFERENCES

[1] Martha's Vineyard Commission, "Suggestions For a Revised Propulsion Study," 8/24/2022.

[2] Elliott Bay Design Group, *13098-004-043-0 M/V Woods Hole Construction Cost Estimate, Rev A,* 2014.

[3] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023. [Online]. Available: https://www.eia.gov/outlooks/aeo/data/browser/.

[4] KPFF, Andy Bennett, "2023.03.23 SSA Energy Costs Memo," 2023.

[5] NWE, *SSA Third Party Capital Cost Review,* 2023.

[6] KPFF, "2100492.001 Martha's Vineyard and Nantucket Steamship Authority Shoreside Electrification Feasibility Study".

APPENDIX A

Capital Cost

CONSTRUCTION COST

Cost Based on 2014 Estimate

Vessel Construction Estimate	Cost - 2014	Inflation Rate	Inflation Cost	Total
Project Management and Administration	$ 2,506,630	3.0%	$ 763,954	$ 3,270,584
Hull & Superstructure	$ 8,282,510	3.0%	$ 2,524,287	$ 10,806,797
Propulsion Machinery	-	-	-	-
Electrical System	$ 3,296,190	3.0%	$ 1,004,590	$ 4,300,780
Electronic & IC Systems	$ 1,832,650	3.0%	$ 558,543	$ 2,391,193
Auxiliary Systems	$ 6,130,070	3.0%	$ 1,868,281	$ 7,998,351
Outfitting	$ 6,612,190	3.0%	$ 2,015,218	$ 8,627,408
Integration & Engineering	$ 3,322,210	3.0%	$ 1,012,521	$ 4,334,731
Shipyard Support Services	$ 2,299,030	3.0%	$ 700,683	$ 2,999,713
Margins	$ 2,520,050	3.0%	$ 768,044	$ 3,288,094
Total Construction Cost				**$ 48,017,649**

MARTHA'S VINEYARD

Diesel Mechanical

Item	Cost Per Unit		Unit	Total
Engines	$ 401	per kW	5120	$ 2,050,865
CPP System & Gears	$ 398	per kW	5120	$ 2,035,319
Ship Service Generator	$ 423	per kW	900	$ 381,000
Systems Margin	25%	% of Prop. Mach.	$ 4,467,184	$ 1,116,796
Total Investment Cost				**$ 5,583,981**

Battery Power at Berths

Item	Cost Per Unit		Unit	Total
Batteries	$ 650	Qty	181	$ 117,633
DC Grid / Drive System	$ 2,899,004	Qty	1	$ 2,899,004
Motors, Propulsion	$ 155,811	Qty	1	$ 155,811
Switchgear and Transformer	$ 248,685	Qty	1	$ 248,685
Integrator Execution, Commissioning, Engineering	20%	% of Ele. Equip.	$ 3,421,133	$ 684,227
Generators	$ 1,304,698	Qty	3	$ 3,914,093
Propellers	$ 50,000	Qty	2	$ 100,000
Reduction Gear	$ 200,000	Qty	2	$ 400,000
Systems Margin	25%	% of Prop. Mach.	$ 7,835,226	$ 1,958,806
Total Investment Cost				**$ 10,478,259**

Peak Shaving

Item	Cost Per Unit		Unit	Total
Batteries	$ 650	Qty	1897	$ 1,233,277
DC Grid / Drive System	$ 2,899,004	Qty	1	$ 2,899,004
Motors, Propulsion	$ 155,811	Qty	1	$ 155,811
Switchgear and Transformer	$ 248,685	Qty	1	$ 248,685
Integrator Execution, Commissioning, Engineering	20%	% of Ele. Equip.	$ 4,536,777	$ 907,355
Generators	$ 1,304,698	Qty	3	$ 3,914,093
Propellers	$ 50,000	Qty	2	$ 100,000
Reduction Gear	$ 200,000	Qty	2	$ 400,000
Systems Margin	25%	% of Prop. Mach.	$ 8,950,869	$ 2,237,717
Total Investment Cost				**$ 12,095,942**

50 Percent Battery Operation

Item	Cost Per Unit		Unit	Total
Batteries	$ 650	Qty	2509	$ 1,630,684
DC Grid / Drive System	$ 2,899,004	Qty	1	$ 2,899,004
Motors, Propulsion	$ 155,811	Qty	1	$ 155,811
Switchgear and Transformer	$ 248,685	Qty	1	$ 248,685
Integrator Execution, Commissioning, Engineering	20%	% of Ele. Equip.	$ 4,934,184	$ 986,837
Generators	$ 1,304,698	Qty	3	$ 3,914,093
Propellers	$ 50,000	Qty	2	$ 100,000
Reduction Gear	$ 200,000	Qty	2	$ 400,000
Systems Margin	25%	% of Prop. Mach.	$ 9,348,277	$ 2,337,069
Total Investment Cost				**$ 12,672,183**

All Battery with Shore Charging

Item	Cost Per Unit		Unit	Total
Batteries	$ 650	Qty	5380	$ 3,497,276
DC Grid / Drive System	$ 2,899,004	Qty	1	$ 2,899,004
Shore charging modifications	$ 1,105,128	Qty	1	$ 1,105,128
Motors, Propulsion	$ 155,811	Qty	1	$ 155,811
Switchgear and Transformer	$ 248,685	Qty	1	$ 248,685
Integrator Execution, Commissioning, Engineering	20%	% of Ele. Equip.	$ 7,905,904	$ 1,581,181
Generators	$ 1,304,698	Qty	1	$ 1,304,698
Propellers	$ 50,000	Qty	2	$ 100,000
Reduction Gear	$ 200,000	Qty	2	$ 400,000
Systems Margin	25%	% of Prop. Mach.	$ 8,605,474	$ 2,151,368
Total Investment Cost				**$ 13,443,151**

Plug-In Hybrid

Item	Cost Per Unit		Unit	Total
Batteries	$ 650	Qty	2775	$ 1,803,459
DC Grid / Drive System	$ 2,899,004	Qty	1	$ 2,899,004
Shore charging modifications	$ 1,105,128	Qty	1	$ 1,105,128
Motors, Propulsion	$ 155,811	Qty	1	$ 155,811
Switchgear and Transformer	$ 248,685	Qty	1	$ 248,685
Integrator Execution, Commissioning, Engineering	20%	% of Ele. Equip.	$ 6,212,087	$ 1,242,417
Generators	$ 1,304,698	Qty	2	$ 2,609,395
Propellers	$ 50,000	Qty	2	$ 100,000
Reduction Gear	$ 200,000	Qty	2	$ 400,000
Systems Margin	25%	% of Prop. Mach.	$ 8,216,354	$ 2,054,089
Total Investment Cost				**$ 12,617,988**

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Diesel Mechanical

Item	Cost Per Unit		Unit	Total
Engines	$ 401	per kW	5120	$ 2,050,865
CPP System & Gears	$ 398	per kW	5120	$ 2,035,319
Ship Service Generator	$ 423	per kW	900	$ 381,000
Systems Margin	25%	% of Prop. Mach.	$ 4,467,184	$ 1,116,796
Total Investment Cost				**$ 5,583,981**

Battery Power at Berths

Item	Cost Per Unit		Unit	Total
Batteries	$ 650	Qty	191	$ 124,268
DC Grid / Drive System	$ 2,899,004	Qty	1	$ 2,899,004
Motors, Propulsion	$ 187,048	Qty	1	$ 187,048
Switchgear and Transformer	$ 248,685	Qty	1	$ 248,685
Integrator Execution, Commissioning, Engineering	20%	% of Ele. Equip.	$ 3,459,005	$ 691,801
Generators	$ 1,304,698	Qty	3	$ 3,914,093
Propellers	$ 50,000	Qty	2	$ 100,000
Reduction Gear	$ 200,000	Qty	2	$ 400,000
Systems Margin	25%	% of Prop. Mach.	$ 7,873,098	$ 1,968,274
Total Investment Cost				**$ 10,533,173**

Peak Shaving

Item	Cost Per Unit		Unit	Total
Batteries	$ 650	Qty	1509	$ 980,941
DC Grid / Drive System	$ 2,899,004	Qty	1	$ 2,899,004
Motors, Propulsion	$ 187,048	Qty	1	$ 187,048
Switchgear and Transformer	$ 248,685	Qty	1	$ 248,685
Integrator Execution, Commissioning, Engineering	20%	% of Ele. Equip.	$ 4,315,678	$ 863,136
Generators	$ 1,304,698	Qty	3	$ 3,914,093
Propellers	$ 50,000	Qty	2	$ 100,000
Reduction Gear	$ 200,000	Qty	2	$ 400,000
Systems Margin	25%	% of Prop. Mach.	$ 8,729,771	$ 2,182,443
Total Investment Cost				**$ 11,775,349**

50 Percent Battery Operation

Item	Cost Per Unit		Unit	Total
Batteries	$ 650	Qty	1826	$ 1,186,589
DC Grid / Drive System	$ 2,899,004	Qty	1	$ 2,899,004
Motors, Propulsion	$ 187,048	Qty	1	$ 187,048
Switchgear and Transformer	$ 248,685	Qty	1	$ 248,685
Integrator Execution, Commissioning, Engineering	20%	% of Ele. Equip.	$ 4,521,326	$ 904,265
Generators	$ 1,304,698	Qty	3	$ 3,914,093
Propellers	$ 50,000	Qty	2	$ 100,000
Reduction Gear	$ 200,000	Qty	2	$ 400,000
Systems Margin	25%	% of Prop. Mach.	$ 8,935,419	$ 2,233,855
Total Investment Cost				**$ 12,073,539**

APPENDIX B

Operating Cost

MARTHA'S VINEYARD

System Properties

System Property	Unit	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation	All Battery with Shorepower	Hybrid
Engine Size	kW	2560.00	0.00	0.00	0.00	0.00	0.00
No. Engines	-	2	0	0	0	0	0
Engines Operating	-	2	0	0	0	0	0
Vessel Operating Hours	hr	5187	0	0	0	0	1
Annual Engine Hours (ea.)	hr	3192	0	0	0	0	0
Generator Size	kW	300	2450	2450	2450	0	2450
No. Generators	-	3	3	3	3	0	2
Generators Operating	-	1	2	1	2	0	1
Annual Generator Hours (ea.)	hr	1729	2128	1729	1108	0	831
Battery Bank	kWh	n/a	181	1897	2509	5380	2775
Cycle Life	yr	n/a	10.00	10.00	10.00	10.00	10.00
Fuel Consumption	gal/trip	95.87	88.78	88.11	88.26	0.00	40.20
Shore Power Consumption	kWh/trip	0.00	0.00	0.00	0.00	1533.08	813.58

Annual Fluid / Shore Power Consumption

Fluid	Unit	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation	All Battery with Shorepower	Hybrid
Diesel	gal	382506	354237	351571	352164	0	160411
Urea	gal	19125	17712	17579	17608	0	8021
Lube Oil (Consumption)	gal	593	354	352	352	0	160
Shore Power	kWh	0	0	0	0	6116979	3246167

Annual Costs

Annual Cost Item	$/unit	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation	All Battery with Shorepower	Hybrid
Diesel	$ 2.15	$822,388	$761,609	$755,878	$757,152	$0	$344,884
Shore Power	$ 0.16	$0	$0	$0	$0	$972,600	$516,141
Urea	$ 3.23	$61,775	$57,209	$56,779	$56,874	$0	$25,906
Lube Oil	$ 8.00	$4,745	$2,834	$2,813	$2,817	$0	$1,283
Battery Maintenance		$0	$4,524	$47,434	$62,719	$134,511	$69,364
Engine Maintenance		$80,539	$0	$0	$0	$0	$0
Reduction Gear Maint.		$4,000	$4,000	$4,000	$4,000	$4,000	$4,001
Generator Maint.		$5,112	$53,693	$43,625	$27,965	$0	$20,974
Motor Maint.		$0	$4,000	$4,000	$4,000	$4,000	$4,000
Total Annual Cost		$978,559	$887,869	$914,528	$915,527	$1,115,110	$986,552

Net Present Value of Operating Costs

Annual Cost Item	Inflation Rate	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation	All Battery with Shorepower	Hybrid
Diesel	2.40%	$22,118,968	$20,484,243	$20,330,100	$20,364,382	$0	$9,276,001
Shore Power	2.00%	$0	$0	$0	$0	$25,076,845	$13,307,816
Urea	3.00%	$1,771,482	$1,640,559	$1,628,214	$1,630,959	$0	$742,904
Lube Oil	3.00%	$136,082	$81,266	$80,655	$80,791	$0	$36,800
Battery Maintenance	3.00%	$0	$129,743	$1,360,232	$1,798,550	$3,857,292	$1,989,111
Engine Maintenance	3.00%	$2,309,570	$0	$0	$0	$0	$0
Reduction Gear Maint.	3.00%	$114,706	$114,706	$114,706	$114,706	$114,706	$114,735
Generator Maint.	3.00%	$146,604	$1,539,713	$1,251,017	$801,934	$0	$601,451
Motor Maint.	3.00%	$0	$114,706	$114,706	$114,706	$114,706	$114,706
Overhaul Item	Inflation Rate						
Engine Overhaul, 10 Yr	3.00%	$2,756,191	$0	$0	$0	$0	$0
Generator Overhaul, 10 Yr	3.00%	$512,032	$5,260,213	$5,260,213	$5,260,213	$0	$3,506,809
Battery Overhaul, 10 Yr	3.00%	$0	$158,089	$1,657,421	$2,191,504	$4,700,047	$2,423,699
Total PV of Operating Costs		$29,866,000	$29,524,000	$31,798,000	$32,358,000	$33,864,000	$32,115,000

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System Properties

System Property	Unit	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation
Engine Size	kW	2560.00	0.00	0.00	0.00
No. Engines	-	2	0	0	0
Engines Operating	-	2	0	0	0
Vessel Operating Hours	hr	3280	0	0	0
Annual Engine Hours (ea.)	hr	2680	0	0	0
Generator Size	kW	300	2450	2450	2450
No. Generators	-	3	3	3	3
Generators Operating	-	1	2	1	2
Annual Generator Hours (ea.)	hr	1093	1787	1093	1333
Battery Bank	kWh	n/a	191	1509	1826
Cycle Life	yr	n/a	10.00	10.00	10.00
Fuel Consumption	gal/trip	299.72	277.78	274.70	276.28
Shore PowerConsumption	kWh/trip	0.00	0.00	0.00	0.00

Annual Fluid / Shore Power Consumption

Fluid	Unit	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation
Diesel	gal	359663	333340	329642	331540
Urea	gal	17983	16667	16482	16577
Lube Oil (Consumption)	gal	537	333	330	332
Shore Power	kWh	0	0	0	0

Annual Costs

Annual Cost Item	$/unit	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation
Diesel	$ 2.15	$773,275	$716,682	$708,731	$712,810
Shore Power	$ 0.12	$0	$0	$0	$0
Urea	$ 3.23	$58,086	$53,834	$53,237	$53,544
Lube Oil	$ 8.00	$4,292	$2,667	$2,637	$2,652
Battery Maintenance		$0	$4,780	$37,729	$45,638
Engine Maintenance		$67,620	$0	$0	$0
Reduction Gear Maint.		$4,000	$4,000	$4,000	$4,000
Generator Maint.		$3,233	$45,080	$27,586	$33,642
Motor Maint.		$0	$4,000	$4,000	$4,000
Total Annual Cost		$910,506	$831,043	$837,920	$856,286

Net Present Value of Operating Costs

Annual Cost Item	Inflation Rate	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation
Diesel	2.40%	$20,798,020	$19,275,887	$19,062,036	$19,171,767
Shore Power	2.00%	$0	$0	$0	$0
Urea	3.00%	$1,665,689	$1,543,783	$1,526,656	$1,535,444
Lube Oil	3.00%	$123,089	$76,472	$75,624	$76,059
Battery Maintenance	3.00%	$0	$137,061	$1,081,921	$1,308,739
Engine Maintenance	3.00%	$1,939,113	$0	$0	$0
Reduction Gear Maint.	3.00%	$114,706	$114,706	$114,706	$114,706
Generator Maint.	3.00%	$92,705	$1,292,742	$791,081	$964,733
Motor Maint.	3.00%	$0	$114,706	$114,706	$114,706
Overhaul Item	Inflation Rate				
Engine Overhaul, 10 Yr	3.00%	$2,756,191	$0	$0	$0
Generator Overhaul, 10 Yr	3.00%	$512,032	$5,260,213	$5,260,213	$5,260,213
Battery Overhaul, 10 Yr	3.00%	$0	$167,006	$1,318,303	$1,594,677
Total PV of Operating Costs		$28,002,000	$27,983,000	$29,346,000	$30,142,000

APPENDIX C

Lifecycle Costs

MARTHA'S VINEYARD

Lifecycle Cost

Cost	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation	All Battery with Shorepower	Hybrid
Capital Cost, Construction and Propulsion Sys.	$ 53,601,630	$ 58,495,908	$ 60,113,591	$ 60,689,833	$ 61,460,801	$ 60,635,638
Total PV of Operating Costs	$ 29,866,000	$ 29,524,000	$ 31,798,000	$ 32,358,000	$ 33,864,000	$ 32,115,000
Lifecycle Cost	$ 83,467,630	$ 88,019,908	$ 91,911,591	$ 93,047,833	$ 95,324,801	$ 92,750,638

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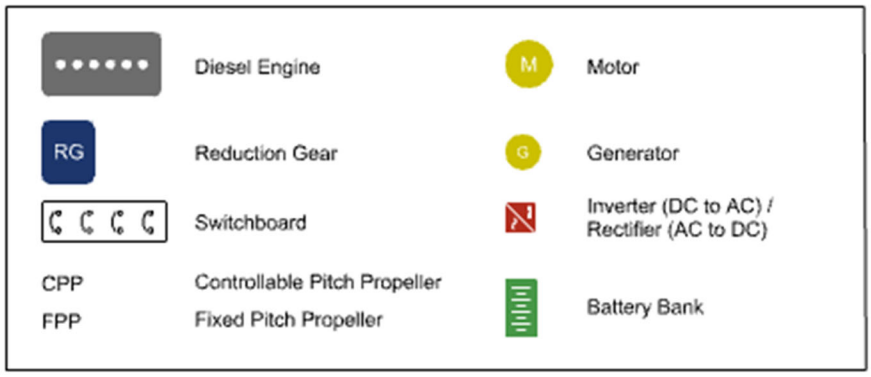
Lifecycle Cost

Cost	Diesel Mechancial	Battery Power at Berths	Peak Shaving	50 Percent Battery Operation
Capital Cost, Construction and Propulsion Sys.	$ 53,601,630	$ 58,550,823	$ 59,792,998	$ 60,091,188
Total PV of Operating Costs	$ 28,002,000	$ 27,983,000	$ 29,346,000	$ 30,142,000
Lifecycle Cost	$ 81,603,630	$ 86,533,823	$ 89,138,998	$ 90,233,188

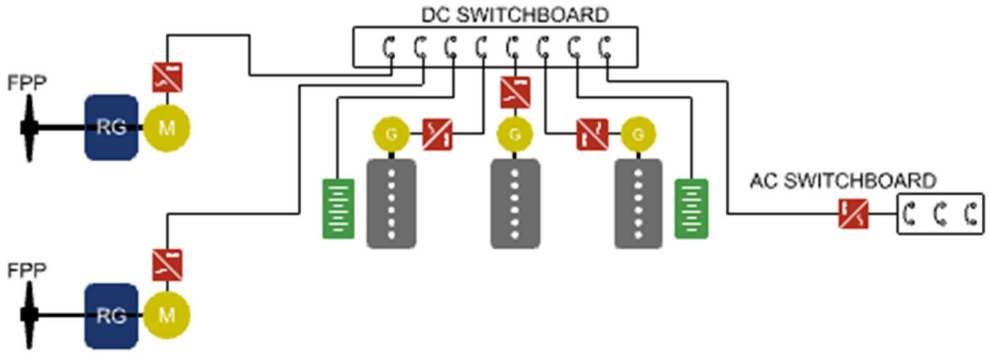
APPENDIX D

System Sketches



DIESEL MECHANICAL, CPP

DIESEL HYBRID, FPP



Note that Options 2-6 are each a variation of the Diesel Hybrid arrangement with the quantity of batteries, generators and a shore power connection as variables.

Elliott Bay
Design Group